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THE MECHANICAL PERFORMANCE OF CROSS-PLIED FIBER GLASS-EPOXY COMPOSITES

BY

ORI ISHAI AND R. E. LAVENGOOD

PROGRAM MANAGER
ROLF BUCHDAHL

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FOREWORD

The research reported herein was conducted by the staff of Monsanto/Washington University Association under the sponsorshio of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR 356-484/4-13-66, entitled "Development of High Performance Composites."

The prime contractor is Monsanto Research Corporation. The Program Manager is Dr. Rolf Buchdahl (Phone-314-694-4721).

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THE MECHANICAL PERFORMANCE
OF CROSS-PLIED FIBER GLASS-EPOXY COMPOSITES

Ori Ishai and R. E. Lavengood

A B S T R A C T

Tensile tests were conducted on glass epoxy cross-ply laminates having either predominantly brittle or ductile epoxy matrices. The ductile system exhibits far better mechanical performance than the brittle counterpart, especially when the transverse plies are on the outside. This was reflected by significantly higher initial and ultimate strength values, slower crack propagation in the transverse layer, higher strains at failure and better toughness at off-axis orientations. In both ductile and brittle systems the laminae have higher strength, stiffness and toughness than their unidirectional references. This improved performance is a result of the interaction between the two perpendicular layers which gives them additional stiffness due to shear and transverse coupling effects and also increases the resistance of each individual layer to crack propagation and plastic flow.

(Contribution HPC 69-99 from the Monsanto/Washington University Association sponsored by the Advanced Research Projects Agency, Department of Defense, under ONR Contract N00014-67-C-0218.)

THE MECHANICAL PERFORMANCE OF CROSS-PLIED FIBER GLASS-EPOXY COMPOSITES

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INTRODUCTION

Unidirectional glass-epoxy composites are among the strongest structural materials available today, however they are of limited usefulness because of their extreme anisotropy. Frequently the strength of such systems is 25 times as great in the direction of the fibers as in the transverse direction. Furthermore, even slight variations in the alignment of the major fiber axis ($\pm$ 7°) can change the load carrying capacity of the composite by as much as a factor of three [1,2]. Thus, for most practical applications, multidirectional composites are necessary, despite the fact that shifting part of the fibers away from the major stress axis decreases the theoretical efficiency of the composite. The orthotropic cross-plies discussed in this paper offer a reasonable compromise between the extreme anisotropy of the unidirectional system and the quasi-isotropy of the random one.

The concepts and theories necessary for engineering design with cross-plied composites were outlined by Waddoups [3], who compared them with conventional structural materials. In his paper it is pointed out that one of the main drawbacks of glass-epoxy cross-ply composites is the premature failure of transverse plies. This results from a mismatch in the strain capacity of the longitudinal and transverse layers. For the commonly used glass-epoxy laminates, the ultimate strain of the transverse layer is about 0.5 percent compared with about 2.5 percent for the longitudinal. When a thin specimen is loaded in tension, the strain distribution is nearly uniform through the thickness, so the transverse plies will crack when the composite strain reaches about 0.5 percent. The longitudinal layers, however, remain intact and have the ability to sustain far greater loads.

For aircraft structures, a conservative design philosophy is used and the limiting stress for design is based on this initial cracking rather than catastrophic failure. This means that for glass-epoxy cross-plies less than 20 percent of the load carrying capacity of the system can be utilized and the high strength of the fibers does not contribute directly to the "ultimate" performance when defined in this manner.

The phenomena of initial failure in glass-epoxy systems was previously studied by Broutman [4] who concluded that transverse cracks cause subsequent deterioration if the system is subjected to cyclic loading. In contrast, a study of graphite-epoxy, cross-ply laminates under cyclic loading revealed that no significant reduction in stiffness and strength was found even after pronounced transverse cracking [5].

This apparent anomaly can be explained by the ultimate strains of the laminae. While there is a factor of 5 difference between the longitudinal and transverse ultimate strains in the glass-epoxy system, the two are nearly identical for graphite-epoxy composites.

It is apparent that by matching the ultimate strain of the different layers one can increase the structural utility of the system. In the graphite epoxy system, the close match is a result of the relatively low strain capacity of the longitudinal plies. For composites with higher ultimate longitudinal strain, the mismatch might be minimized by increasing deformability of the transverse laminae.

The objective of this study is to determine the effects of matrix deformational characteristics on the overall mechanical performance of cross-plied composites. Particular emphasis is placed on the effect of the matrix on the strength efficiency of the composites.

Ductile and Brittle Matrix Composites

Composites were prepared with two different matrix resins. The first, Epon 815 plus Versamid 140 (60 to 40 parts by weight) will be referred to as a ductile resin for purposes of identification while the second, Epon 828 plus Shell Curing Agent Z (5 parts to 1), will be called a brittle resin. This arbitrary distinction is based on the stress-strain behavior of the resins.

The ductile resin has a distinct yield point preceding failure while the brittle material, which is typical of the resins used in most glass-epoxy laminates, fails without passing through a yield plateau (Figure 1).

The mechanical characteristics of the unfilled resins and corresponding unidirectional composites were reported in previous papers [6-8], and can be summarized as follows: The brittle resin has higher strength but lower ultimate strain than its ductile counterpart. A unidirectional transverse composite made with the brittle matrix resin, however, has lower strength and ultimate strain than the ductile composites (Figure 1). Off-axis brittle composites have higher strength but significantly lower ultimate strain than the ductile matrix composites (Figure 2). In the longitudinal direction the two composites have almost the same stiffness but the ductile system has somewhat higher strength (Figure 2). The quantitative data for strength, stiffness, and ultimate strain are given in Table I for the two unidirectional systems. Generally it can be concluded that, despite the lower strength of the ductile resin, the composites with this matrix have higher ultimate strains and toughness than the composites made with the brittle matrix.

Experimental Details

The cross-ply laminates were prepared by filament winding on rectangular mandrels 8 inches square and 1/2 inch thick. After the first layer was wound, the mandrel was turned 90° so that the second and third layers were wound perpendicular to the first (see Figure 3). The mandrel was then returned to its original position and the fourth layer wound. A final volume fraction of 56% was established by clamping steel plates on both sides of the mandrel and squeezing out excess resin. The laminates were cured for 30 minutes at 80°C followed by 90 minutes at 150°C.

Straight sided specimens 1/4" and 1/2" wide were cut from the plates at 0°, 20°, 30°, 45°, 60°, 70°, and 90° to the outside fibers. These were tabbed with glass fabric reinforced laminates and tested in tension with an Instron tester at a cross-head speed of 0.2 inch/min (0.067 min^{-1} strain rate in the 3" gauge length of the specimens). An extensometer was used to continuously record strains. All tests are conducted at room temperature (78 to 80°F).

Test Results and Discussion

90° - 0° Laminates*

Typical stress-strain curves for 90° - 0° cross-ply specimens are shown in Figure 4. In general, an abrupt, but minor, decrease

*The notation 90° - 0° refers to specimens in which the fibers in the outer laminae are at 90° to the applied stress and those in the inner laminae are at 0°.

in stiffness is associated with the appearance of the first crack in the transverse layer. The deformation at which this initial cracking (I.C.) occurs in the ductile composite is significantly greater than in the brittle one. In both cases the strain at which initial cracking occurs is about the same as the ultimate transverse strain of the respective unidirectional composites, that is 0.5 percent for the brittle system versus 1.0 percent for the ductile one. The low strength efficiency of the glass-epoxy system when designed on the basis of initial failure is apparent in Figure 4.

The initial cracking of the brittle cross-ply specimens is accompanied by rapid, noisy crack propagation. The first crack is immediately followed by numerous others, all parallel to each other, and within a short time the gauge length is covered with uniformly distributed cracks which are about 0.05 inches apart (Figure 5). Quite a different process is observed in the ductile specimens. Here cracking initiates at about 1.0 percent strain and propagation is slow and without noise. The time interval between cracks is longer, and the gaps between them are wider and irregular. The difference in the crack patterns is apparent in Figure 5. In the ductile system the cracks are not so straight, the spacing is not uniform, and a substantial number of cracks seem to have been arrested in the middle of their propagation path. All of these characteristics point to the presence of an active ductile-plastic mechanism which dissipates part of the input mechanical energy as heat through flow rather than by increasing the surface through crack propagation.

The ultimate stress and strain of the ductile cross-ply are about 10 percent higher than those of the brittle system. Since the transverse layer is already cracked, it should not contribute directly to the ultimate strength. It therefore seems reasonable to attribute this improvement to the fact that the glass fibers are embedded in a ductile matrix.

The Arrangement of Layers

The above data were obtained with specimens made of four layers in which the transverse lamina were at the external surface (90° - 0°). Similar tests were conducted on four-layer specimens with the transverse lamina in the middle (0° - 90°). Results in Table 2 show that when longitudinal layers are on the surface, lower ultimate composite stresses and strains are obtained. This appears to result from an unbalanced load distribution between the two longitudinal surface layers which are separated by the failed middle layers.

45° - 45° Laminates

The 45° - 45° composite represents the minimum stiffness configuration of a balanced cross-ply. Both the brittle and ductile laminates have higher strength and ultimate strain than corresponding unidirectional composites tested off-axis at 45° (Figure 6). The ductile cross-ply has somewhat lower ultimate stress but much higher ultimate strain than the brittle counterpart.

Considerable cracking precedes failure in these specimens, however, because of the balanced construction the cracks occur simultaneously in all four layers. As before, the initial cracks occur at a much lower strain and propagate more rapidly in the brittle specimens than in the ductile ones. In the brittle composites, the cracks continue to form with an increase in strain but with essentially no increase in stress (Figure 6). The relatively wide gaps between the individual cracks is shown in Figure 7. In the ductile composite the cracking starts only after substantial straining $\left(\varepsilon_{ic} = 4.0\%\right)$ and the cracking process is slower. A distribution of fine cracks covers the entire gage length before failure occurs (Figure 7). Continued cracking is accompanied by a slight but a steady stress increase analogous to strain hardening phenomena. A permanent change in the lateral dimension was found in all 45° - 45° specimens tested. A residual width contraction of about 5 percent is typical for the ductile specimens compared with less than 2 percent for the brittle ones.

Cross-Ply Versus Unidirectional Composites

In a cross-plied tensile specimen, two stress and strain values have structural engineering significance. The first is related to the initiation of cracking in the layer having the lowest ultimate strain and the second is related to the catastrophic failure of the specimen. In the 90° - 0° cross-ply specimens, the knee in the stress-strain curve was shown to be a good measure of the ultimate strain of corresponding transverse composites (Figure 7). The same concept can be applied to off axis crossplies. Figure 8 shows that the initial cracking strain of both types of crossplies are nearly the same as the ultimate strain of an equivalent unidirectional composite. The slight superiority of the crossply laminae may indicate some synergism or may merely be a result of our inability to detect the first crack which occurs.

The concept of composite stress, that is, total load divided by the area of the composite has no physical significance as a real stress. In order to compare the characteristics of crossplies with the properties of their unidirectional constituents, the actual stresses and strains must be calculated for each layer. By assuming uniform strain through the thickness of the specimen and a linear stress-strain relationship for the individual layers, one can relate the lamina stresses to the composite stress as follows:

$$\sigma_c = \sigma_j \left(n_{kj} \, c_k + c_j \right) \tag{1}$$

where:

σ_c = P/A = composite stress

σ_j = actual stress acting on the j layer

c_j = ratio of cross sectional area of the j layer to that of the composite

$n_{kj} = E_k/E_j$ = the modular ratio of the k to j layer

If we define the j layer as the one in which initial cracking occurs, the ultimate stress of that layer may be calculated as follows:

$$\sigma_{uc} = \sigma_{ic} / \left(n_{kj} \, C_k + C_j \right) \quad . \tag{2}$$

When the j layer is fully cracked it is reasonable to assume that only the k layer is left to support the load. In this situation, Equations 1 and 2 are no longer meaningful and one can use the following simple relationship for deriving the actual lamina stress at failure:

$$\sigma_{uk} = \sigma_{uc}/c_k \quad . \tag{3}$$

Equations 2 and 3, and the composite stress data given in Table II, were used to calculate the stresses in the individual layers at failure for the various cross-ply laminates. These data may then be compared with the data in Table I for the corresponding unidirectional composites. This comparison is illustrated in Figures 9 and 10 for the brittle and ductile composites, respectively. In both cases the individual layers in the cross-ply laminates are significantly stronger than the unidirectional references. This improvement results from the simultaneous arresting of cracking and flow processes by the criss-crossing fibers. More mechanical energy must be put into the system to overcome these barriers. As a result of these complicated interactions, the strength and toughness of the crossplied composites is far greater than the weighted average of the laminae. Simple summation techniques are clearly not adequate for predicting the strength of multi-directional laminates.

<u>Stiffness</u>

The experimentally observed values of Young's moduli are given in Table II for various cross-ply orientations. The general trend shows a symmetrical decrease in stiffness with a minimum at the 45° - 45° orientation. This decrease is somewhat more pronounced in the ductile composites. The higher stiffness of the brittle system is evident over the entire range. Assuming uniform strain distribution through the thickness and neglecting Poisson and shear coupling effects, one can estimate the stiffness of multidirectional laminates from the data for the unidirectional lamina with the following simple expression:

$$E_c = \sum_{i=1}^{n} E_i C_i \qquad (4)$$

where E_c = the composite laminate tensile Young's modulus,

E_i = the Young's modulus of the i lamina, and

C_i = the ratio of the cross-sectional area of the i lamina to that of the composite.

Using the data given in Table I for the unidirectional lamina at different orientations and Equation 4, the expected moduli of balanced cross-plies at different orientations was calculated. These predicted values are compared with experimental results with the ductile system in Figure 11. The theoretical curve has the same general shape as the experimental one, but the measured stiffness values for the laminates are always higher than that predicted by Equation 4. The same was found foı the brittle system. The higher experimental values (about 20 percent above the theoretical ones) are again the result of interactions between the individual laminae which give rise to additional transverse and shear coupling stresses.

Conclusions

The performance of the individual laminae is significantly better in cross-ply laminates than in unidirectional form. The stiffness of the cross-plies is about 20 percent higher than the average lamina stiffness and the ultimate lamina stress is as much as twice unidirectional lamina strength.

In the off-axis directions, the cross-plies with the brittle matrices have higher stiffness and strength while the ductile matrix composites have higher toughness and strain capacity.

In a 90° - 0 system the use of a ductile matrix in cross-plied composites results in a negligible decrease in stiffness and very significant increases in composite strength. The ultimate strength of the composites is only increased by about 10 percent but the frequently more important initial cracking stress is doubled. For many applications this means that the useable strength is doubled with no sacrifice in materials or fabrication cost.

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LIST OF FIGURES

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Orientation	0°		10°		20°		30°		45°		60°		90°		Unfilled Matrix	
Composite Type	B*	D**	B	D	B	D	B	D	B	D	B	D	B	D	B	D
Ultimate Tensile Stress (K.S.I.)	145	150	45	32	25	18	16	12	11	10	9	9	8	9	12	8
Ultimate Tensile Strain (%)	2.2	2.5	.95	2.2	1.4	1.7	.80	2.1	.85	3.0	.55	1.7	.45	.95	3.5	5.6
Youngs Modulus (M.S.I.)	6.0	6.1	5.6	5.2	3.7	3.3	3.2	2.2	2.2	1.4	1.7	1.2	1.6	1.3	.44	.31

*Brittle
**Ductile

TABLE II. MECHANICAL CHARACTERISTICS OF BRITTLE AND DUCTILE EPOXY-GLASS CROSS PLY LAMINATES

Configuration	90°-0°		0°-90°		70°-20°		60°-30°		45°-45°	
Matrix Type	D*	B**	D	B	D	B	D	B	D	B
Youngs Modulus (M.S.I.)	4.4	4.5	4.3	4.4	3.2	3.6	2.4	2.8	1.9	2.7
Composite Stress at Initial Cracking (K.S.I.)	42	24	30	22	18	13	14	19	12	17
Composite Stress at Ultimate Failure (K.S.I.)	107	72	64	64	21	23	16	20	14	17
Tensile Strain at Initial Cracking (%)	1.0	0.5	0.7	0.5	2.0	0.5	2.0	0.9	3.7	1.3
Ultimate Tensile Strain (%)	3.2	2.1	1.8	1.9	6.5	1.0	6.5	1.6	8.0	3.0

*Ductile
**Brittle

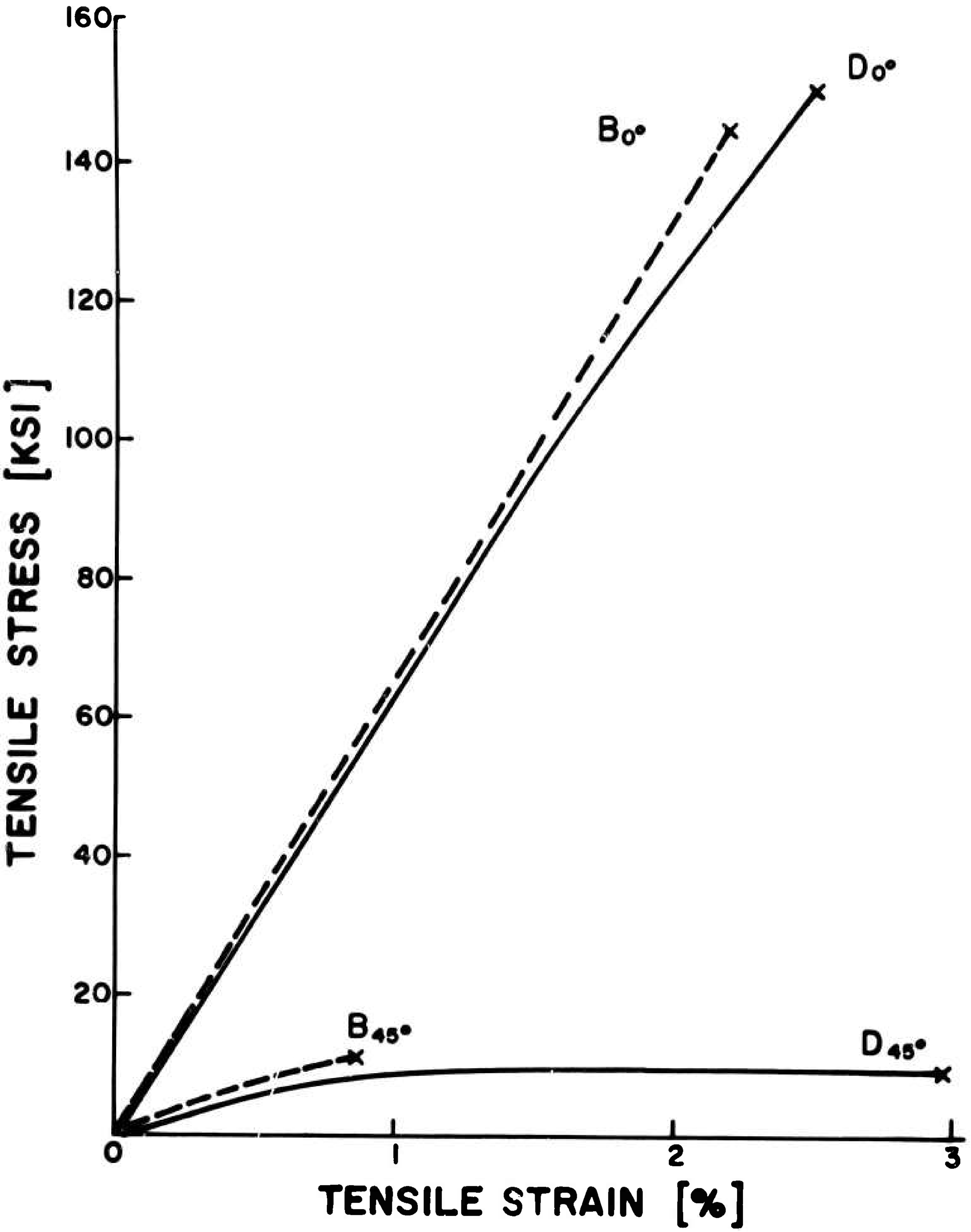


Figure 2. Stress-strain curves for "ductile" and "brittle" unidirectional composites (θ = 0° and θ = 45°).

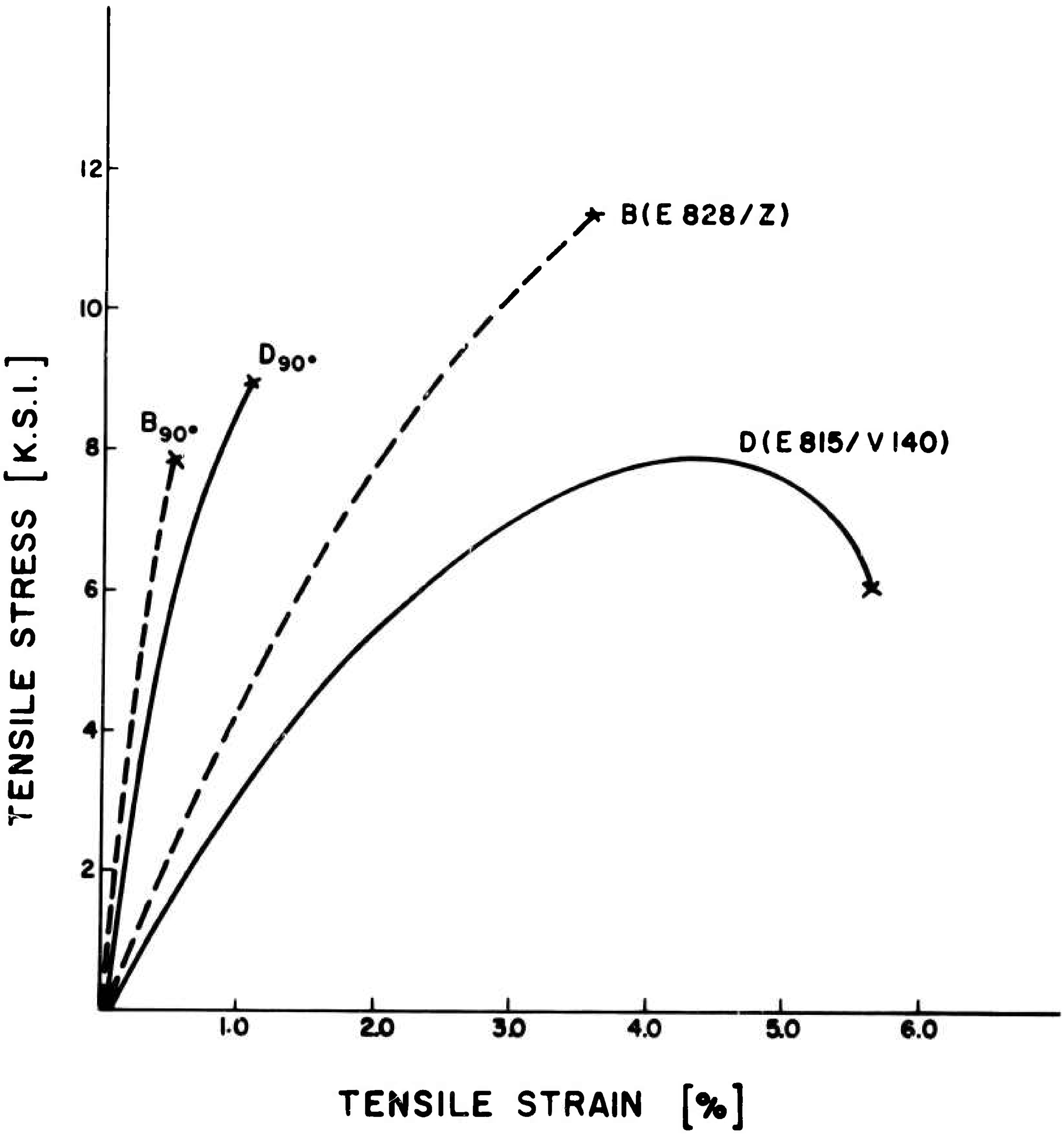


Figure 1. Stress-strain curves for "ductile" and "brittle" epoxy matrices and their respective transverse composites.

CROSSPLY FABRICATION

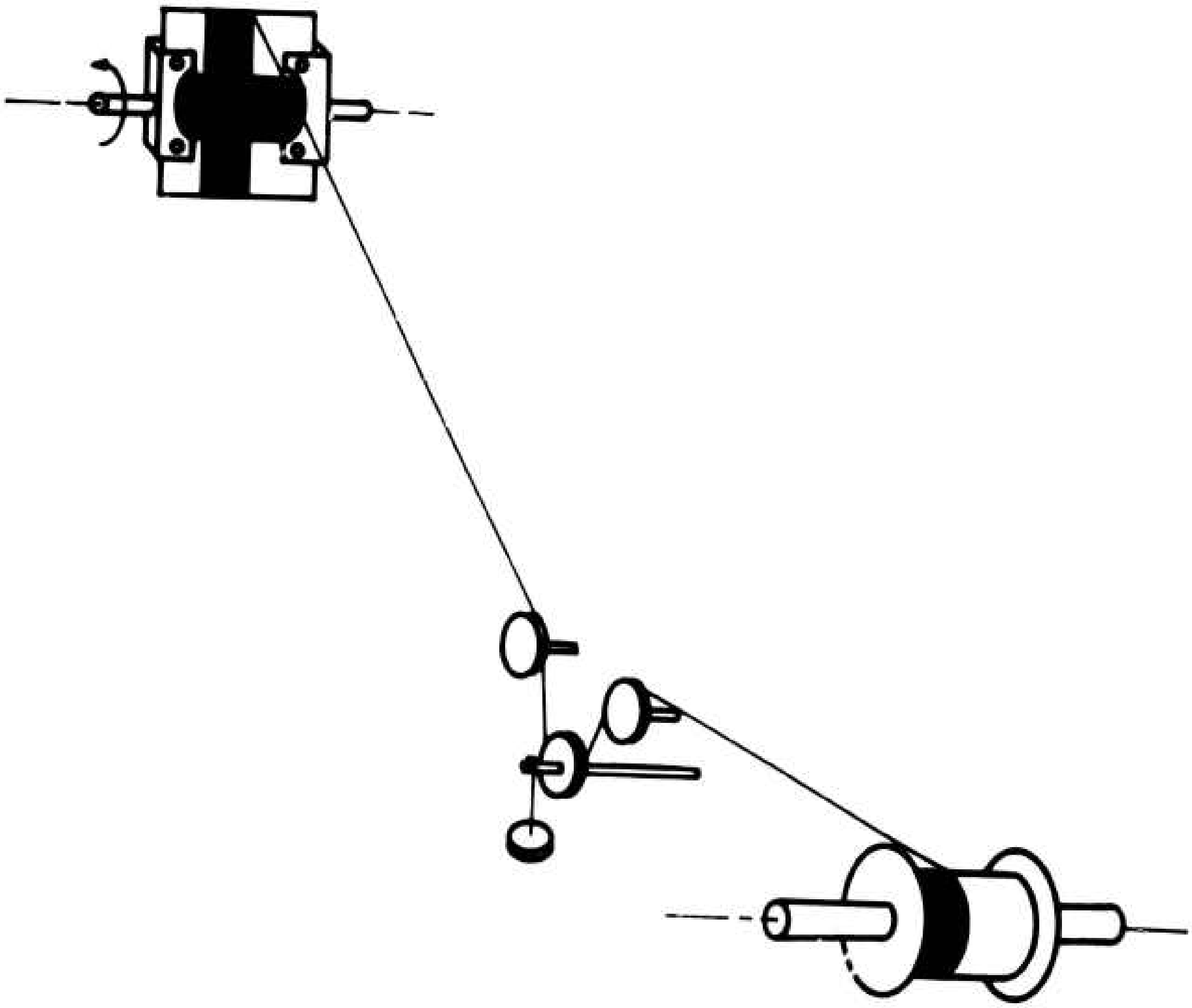


Figure 3. Schematic illustration of cross-ply filament winding set up.

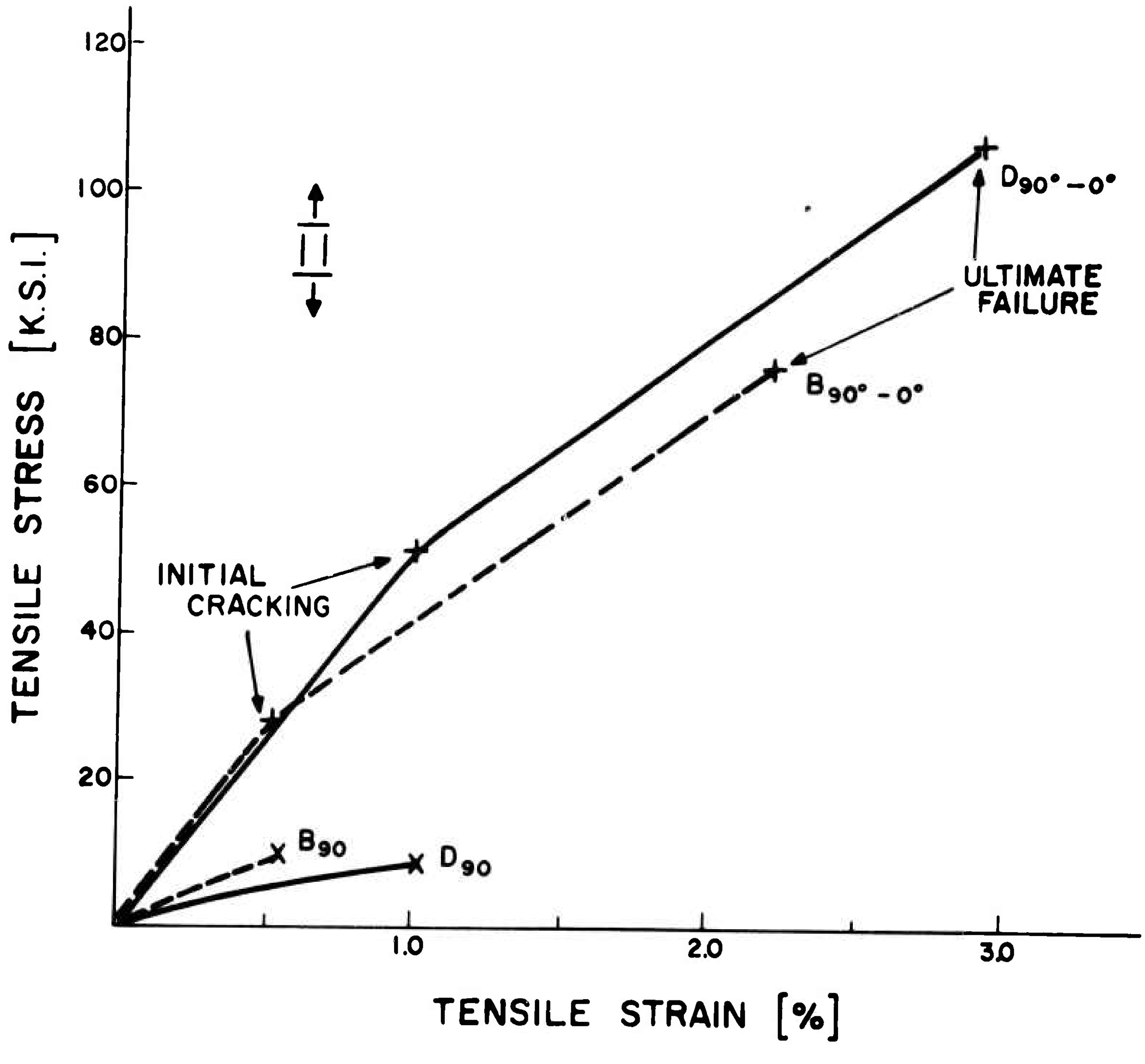


Figure 4. Stress-strain curves of "ductile" and "brittle" 90°-0° cross-ply laminates and their transverse unidirectional references.

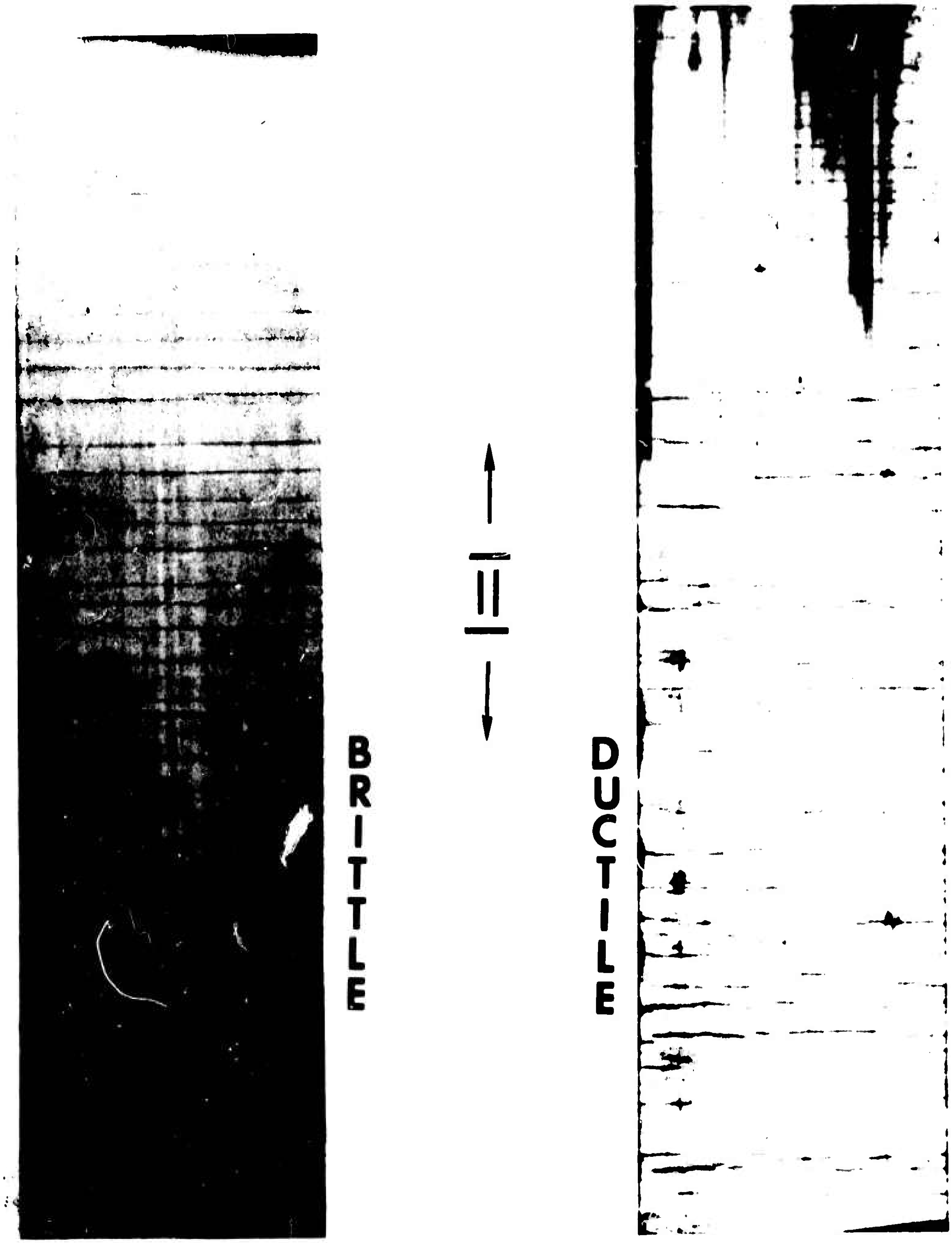


Fig. 5. Photograph of broken 90°-0° cross-ply specimens showing the initial cracking patterns associated with the two

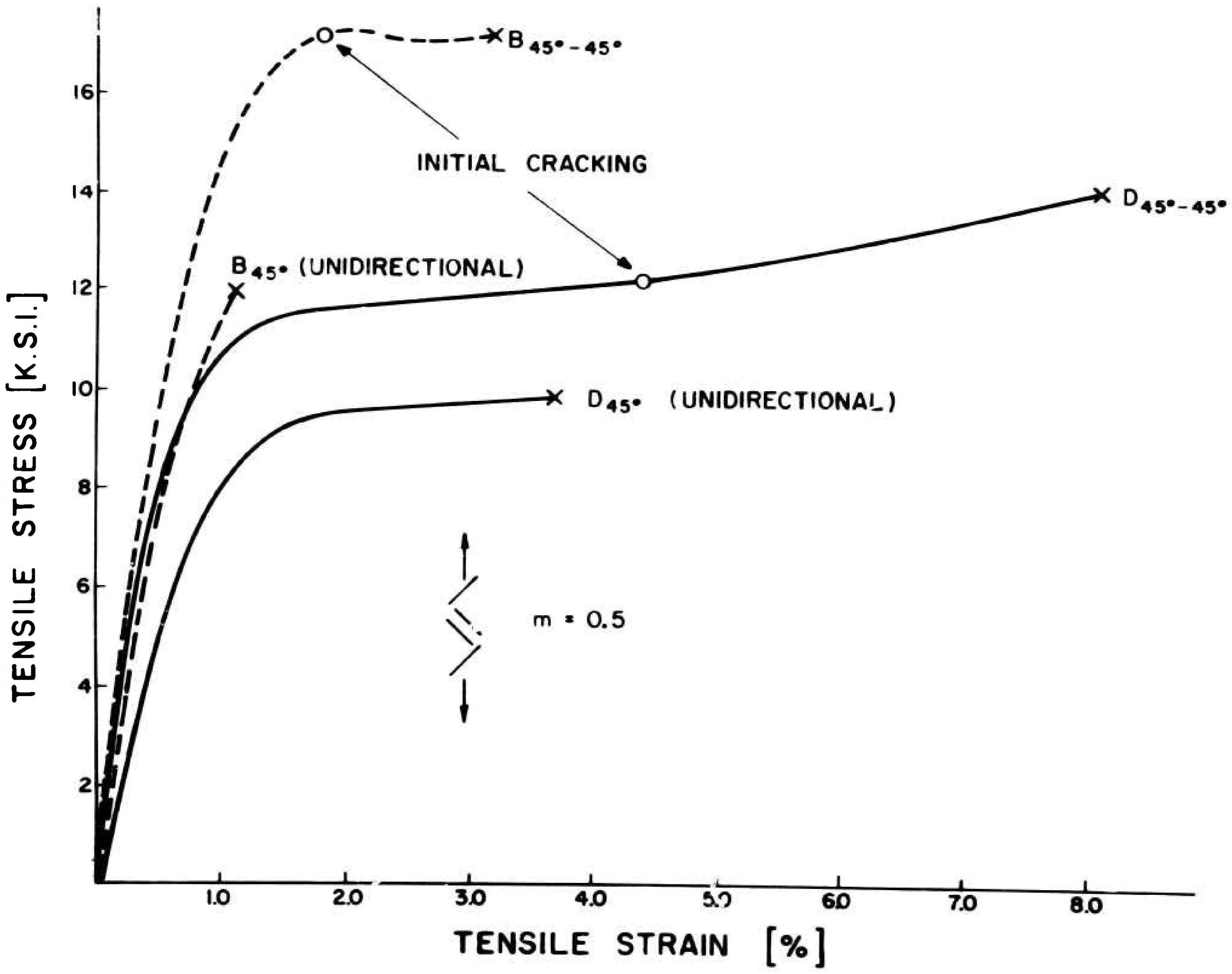


Figure 6. Stress-strain curves of "ductile" and "brittle" 45°-45° cross-ply laminates and their unidirectional references.

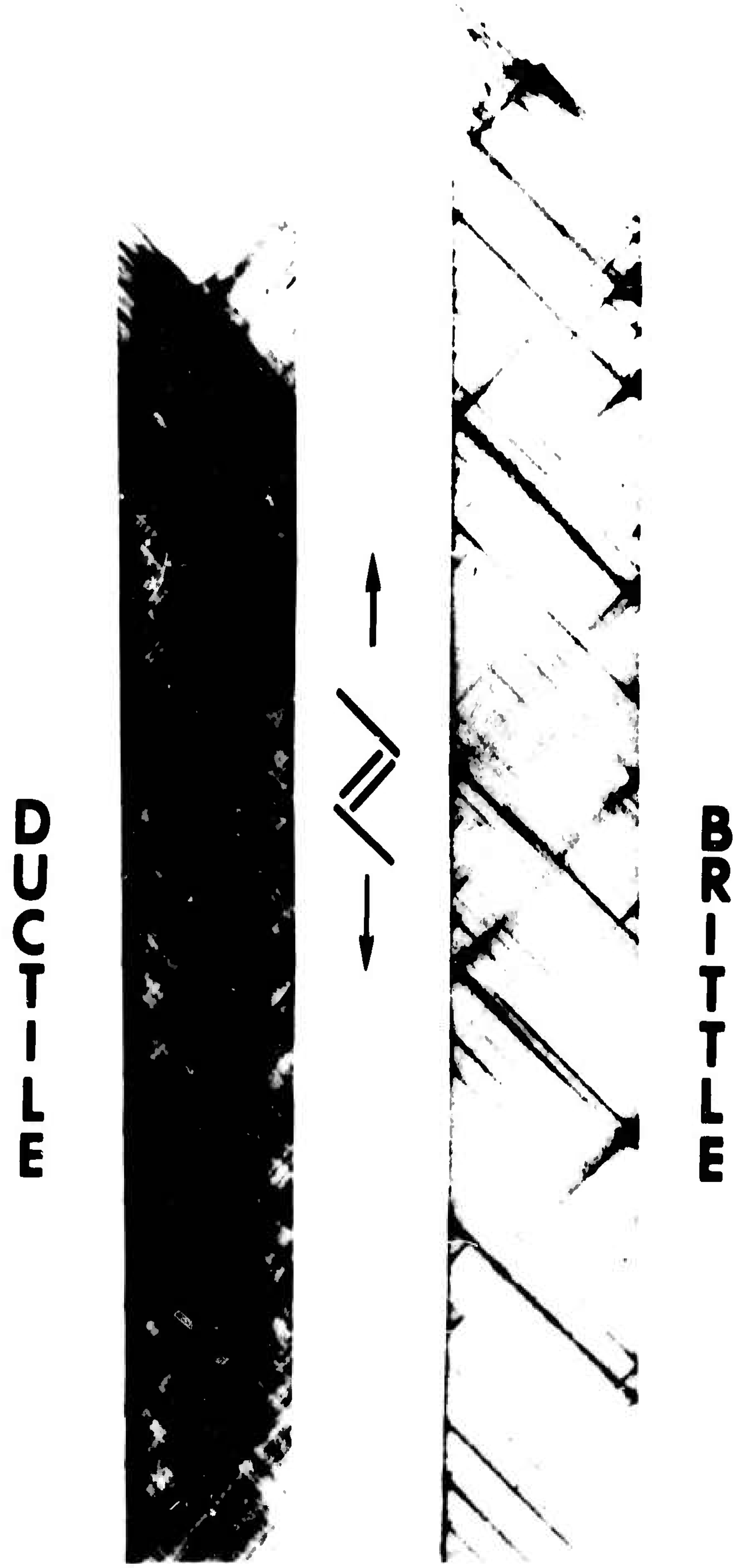


Fig. 7. Photograph of broken 45°-45° laminates showing the initial cracking patterns associated with the two matrices.

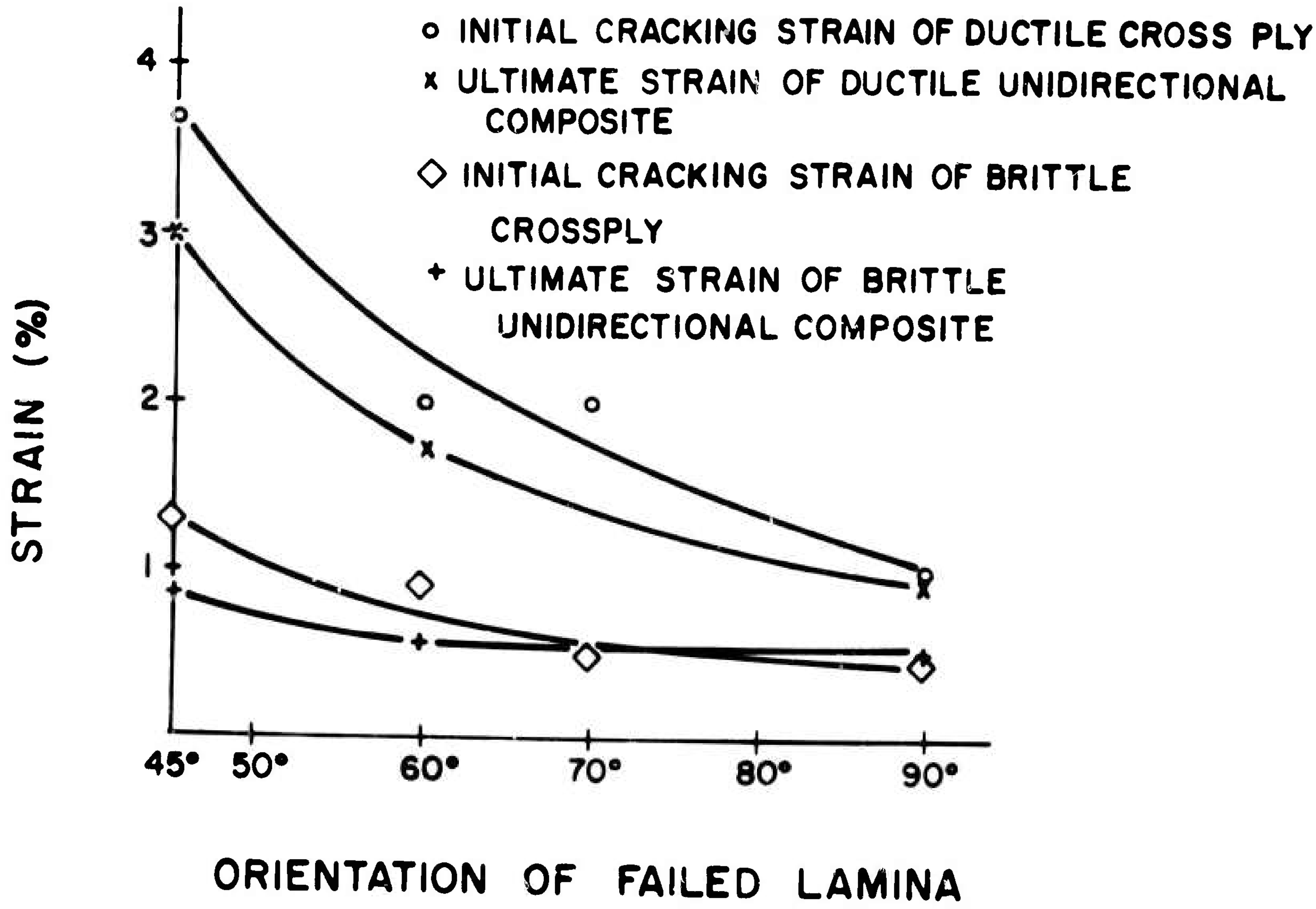
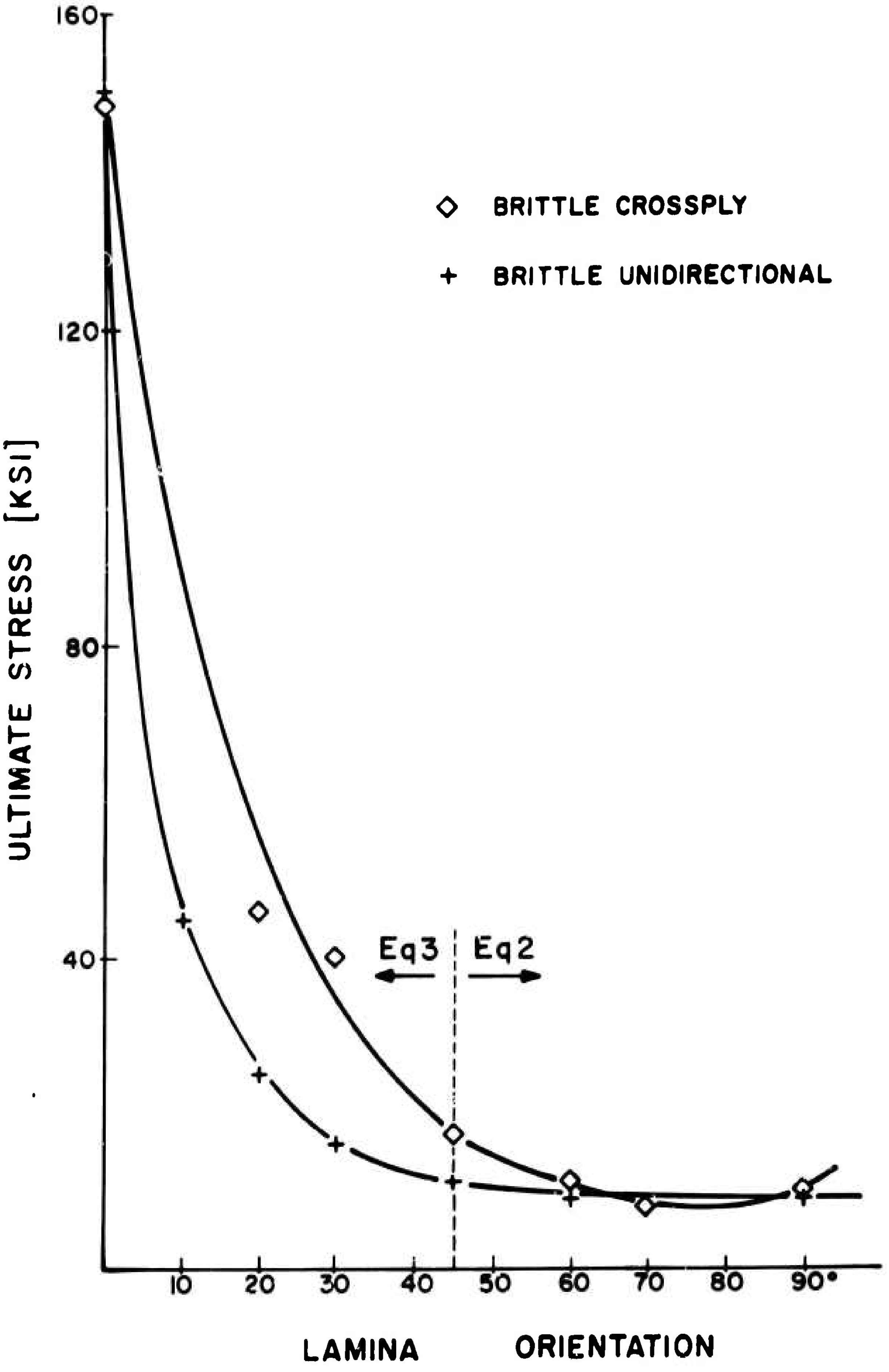


Figure 8. The effect of orientation on ultimate lamina strain in unidirectional and cross-plied composites.



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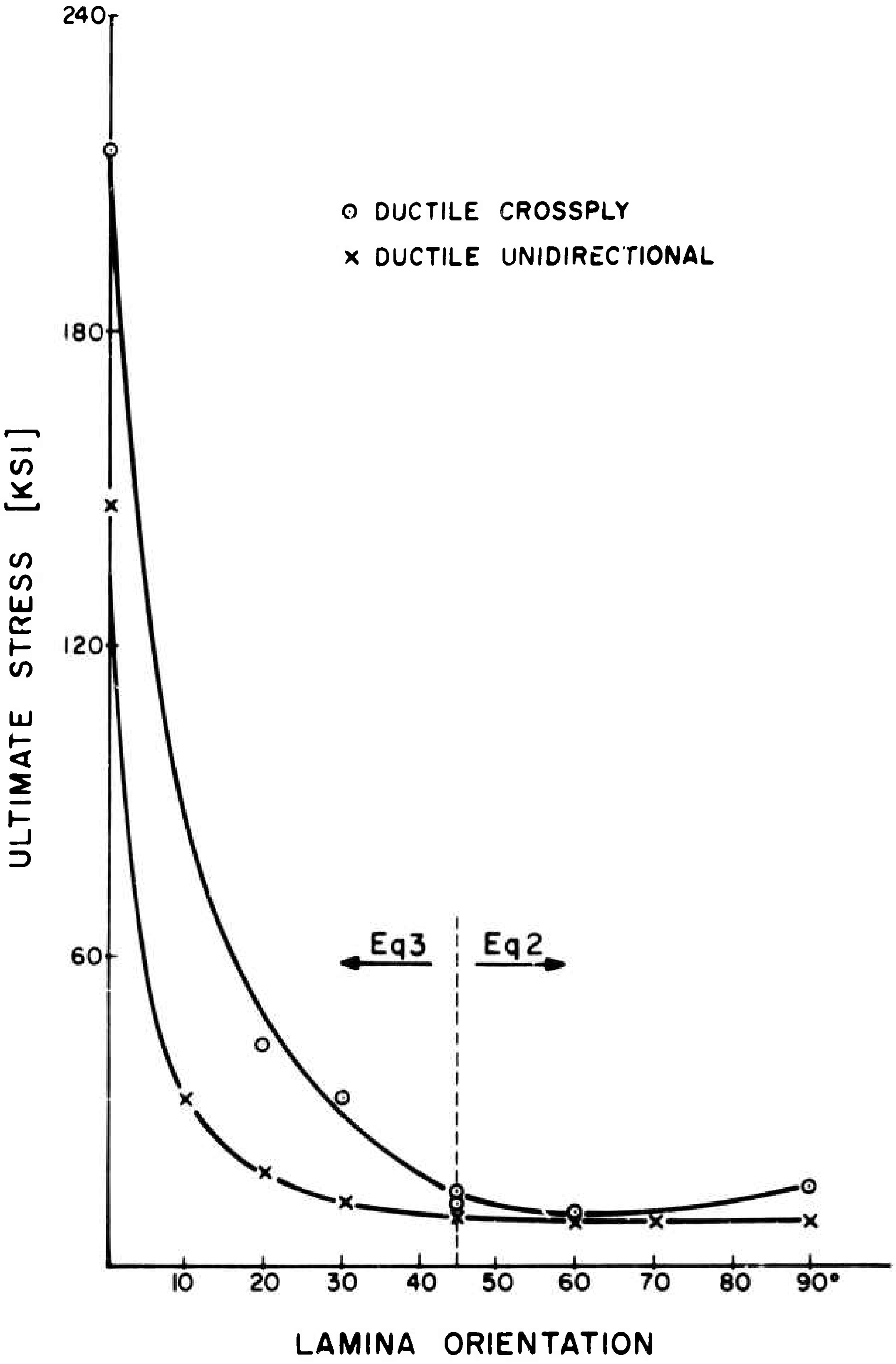

Figure 10. The effect of lamina orientation on ultimate lamina stress in ductile matrix unidirectional and cross-plied composites.

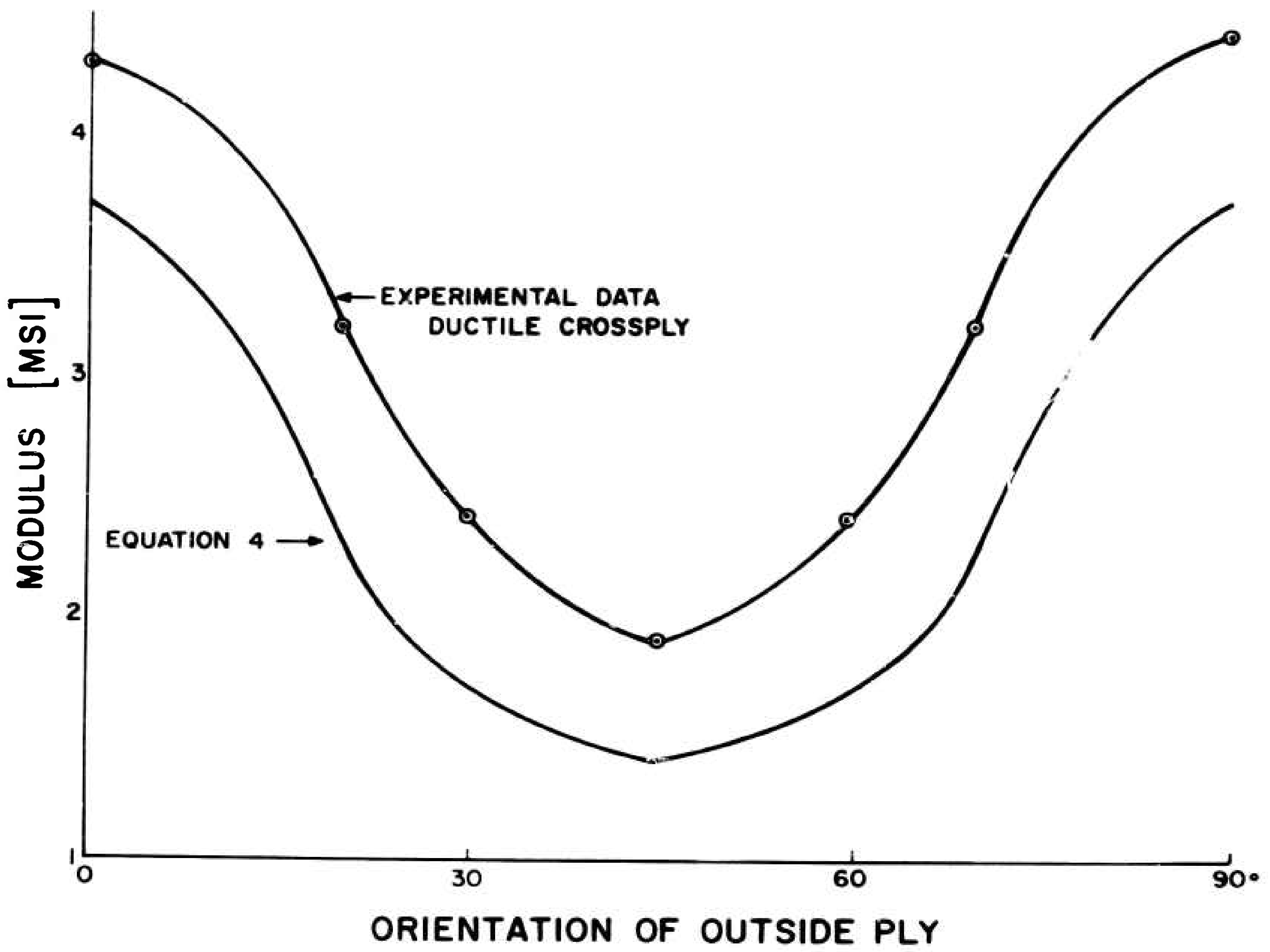

Figure 11. Stiffness versus orientation of cross-ply "brittle" and "ductile" laminates compared with predictions based on a simplified theory ignoring coupling effects.

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13. ABSTRACT

Tensile tests were conducted on glass epoxy cross-ply laminates having either predominantly brittle or ductile epoxy matrices. The ductile system exhibits far better mechanical performance than the brittle counterpart, especially when the transverse plies are on the outside. This was reflected by significantly higher initial and ultimate strength values, slower crack propagation in the transverse layer, higher strains at failure and better toughness at off-axis orientations. In both ductile and brittle systems the laminae have higher strength, stiffness and toughness than their unidirectional references. This improved performance is a result of the interaction between the two perpendicular layers which gives them additional stiffness due to shear and transverse coupling effects and also increases the resistance of each individual layer to crack propagation and plastic flow.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Fiber glass						
epoxy						
fiber reinforced						
cross-ply						
strength						
stiffness						
composite						